Wave Conditions Inducing Extreme Mooring Loads on a Dynamically Responding Moored Structure

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This paper is dedicated to late Prof George Smith, recognising his significant scientific contribution he has made to the Marine Renewable Energy sector.

***Abstract*— The aim of this paper is to determine which wave conditions are inducing extreme mooring loads on a highly dynamically responding moored structure. Currently, the design of a mooring system for a typical oil and gas offshore structure is based on the prediction of the extreme mooring loads for a limited number of wave conditions along the envelope of a wave scatter diagram. During the design process, an inappropriate choice of wave conditions could lead to an incorrect estimation of extreme mooring loads, which may result either in the loss of the mooring system or in a costly overdesign.**

This paper draws on mooring tensions and wave conditions that have been recorded at a mooring test facility using a multi-leg catenary mooring system. The mooring loads have been assessed to identify extreme mooring loads, which have been analysed in respect to the corresponding wave conditions. Further, joint probability distributions of wave conditions that results in extreme mooring loads have been determined.

The most important finding is that extreme mooring loads were not necessarily identified to occur on the envelope of the wave climate parameter scatter diagram.

***Keywords*— Extreme mooring loads, wave condition, scatter diagram, joint probability distribution, MEC, Wave Frequency, mooring, catenary**

I. Introduction

In order to design a conventional mooring system, an assessment of extreme mooring loads should be carried out following standards. For mooring system analysis, DNV-OS-E301 [1] recommends using several sea states with a return period of 100 years, with wave conditions given as a pair of significant wave height Hs and peak period Tp chosen along the 100-year envelope of the Hs/Tp scatter diagram.

A scatter diagram is obtained by classifying and then counting the number of occurrences of Hs and Tp which have been measured or obtained by hindcast model [2]. (eq 1)

$$SDw_{i,j} = \sum_{k=1}^{nb\_sea} \left\langle \begin{matrix} Hs_0 + (i-1)Hs_{bin} \le Hs_k < Hs_0 + iHs_{bin} \\ \text{and} \\ Tp_0 + (j-1)Tp_{bin} \le Tp_k < Tp_0 + jTp_{bin} \end{matrix} \right\rangle \quad (1)$$

With SDw the wave scatter diagram, Hs_k and Tp_k the couple of wave condition for a given sea state k, Hs_0 and Tp_0 the minimum wave conditions considered in the scatter diagram, Hs_{bin} and Tp_{bin} the bin size used by the scatter diagram, nb_sea the total number of sea states considered for this study and i and j the numbers of bins of the scatter diagram.

Minimum values Hs_0 and Tp_0 can be chosen higher than zero due to instrument limitations. The bin size Hs_{bin} and Tp_{bin} and numbers of bins i and j should be chosen depending on the number of sea states recorded in order to find a compromise between resolution and population of the bins.

The joint probability distribution of each Hs/Tp pairs is obtained by dividing the scatter diagram by the total number of sea states considered in the scatter diagram. (eq 2)

$$JPDw_{i,j} = \frac{\sum_{k=1}^{nb\_sea} \left\langle \begin{matrix} Hs_0 + (i-1)Hs_{bin} \le Hs_k < Hs_0 + iHs_{bin} \\ \text{and} \\ Tp_0 + (j-1)Tp_{bin} \le Tp_k < Tp_0 + jTp_{bin} \end{matrix} \right\rangle}{nb\_sea} \quad (2)$$

With JPDw the joint probability distribution of wave conditions.

An envelope line can then be drawn which shows the limitations between the zero values of the matrix of the joint probability distribution, and the non-zero values. Linear interpolation can be used between the zero and non-zero values in order to increase the plot resolution. According to the representative standards, design calculations should be performed for several sea states along the upper part of this envelope (Fig. 1).

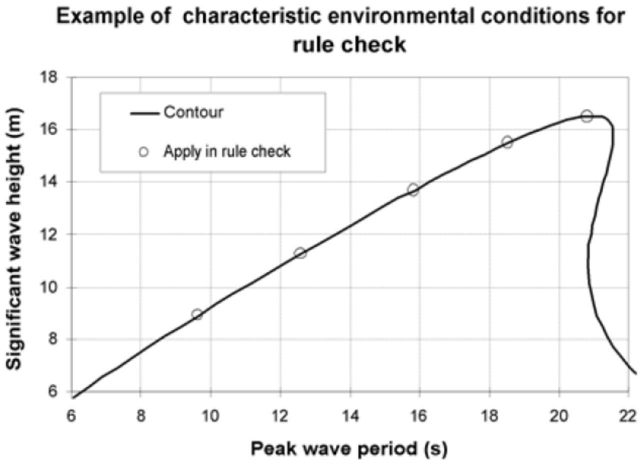


Fig. 1 example of Hs/Tp design envelope given by DNV OS E301 [1]

This paper is assessing the probability distribution of extreme mooring loads over a wide range of wave conditions for highly dynamic floating MECs. Field measurements have been used for this study and are described in part II. The assessment methodology is given in part III. The results are presented in part IV and discussed in part V. This is followed by a conclusion in part V.

II. The South West Mooring Test Facility

The South West Mooring Test Facility (SWMTF) research is led by the mooring and hydrodynamic group at the University of Exeter, working with the Peninsula Research Institute for Marine Renewable Energy (PRIMaRE). This facility has been built to conduct long term sea trials for moorings of MEC devices. It is installed in Falmouth Bay, Cornwall, UK. The location was chosen to provide a site near a port and with wave conditions with an approximate one third scale to the Wave Hub site. The water depth at this site is between 27 m (LAT) and 32.4m (HAT). The deployment position of the buoy is 50°47.5’N 5°2.85’W (Fig. 2).

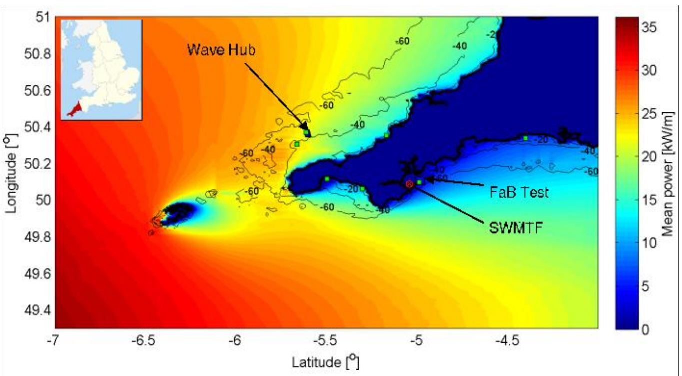


Fig. 2 Location of the SWMTF

This facility has been previously described ([3], [4]). The facility includes:

- An instrumented surface buoy of 3250 kg and 2.9m float diameter (Fig. 4(a)), equipped with conventional axial load cells (Fig. 4(b)) to record mooring load data at 20Hz. This buoy is moored with a three catenary leg mooring system combining chains and nylon rope (Fig. 3). The data are continuously recorded and saved every 10 minutes. The values for the minimum, average, maximum and standard deviation of the mooring load during each 10 minute interval are also saved in a separate file.

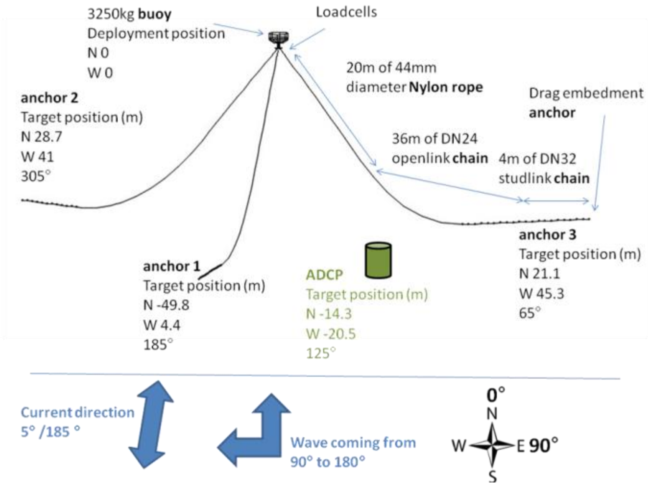


Fig. 3 Mooring layout, ADCP position and direction of the environmental loads at SWMTF


(a) (b)

Fig. 4 Mooring buoy at SWMTF (a) and mooring load cells (b)

- A Workhorse Sentinel Acoustic Current Doppler Profiler (ADCP), equipped with 4 inclined beams to record wave and current data at 2Hz, with a 50 cm bin resolution. (Fig. 5,[5]) The ADCP is installed on the seabed 25m towards the SE direction in respect to the buoy equilibrium position (Fig. 3). The data are continuously recorded and saved every 17.0667 minutes (2048 points). After the recovery of the ADCP, which is retrieved approximately every 3 months, the data are processed using Wavesmon, a software package provided by Teledyne RDI to obtain spectral data for the significant wave height, Hs, the peak period, Tp, the maximum current magnitude and the corresponding current direction in a vertical water column for each 17 minute file.

Fig. 5 ADCP used at SWMTF in its frame

III. METHODOLOGY

A methodology to highlight which wave conditions induced extreme mooring loads during sea trials is developed in this section. It first assesses the joint probability distribution of wave conditions as a reference. Extreme mooring loads were identified and their corresponding wave conditions were recorded. These wave conditions corresponding to extreme mooring loads are then compared to the site overall wave conditions, in order to estimate which wave conditions are inducing extreme mooring loads.

A. Assessment of the site wave conditions

Hs/Tp wave measurements are arranged in a 12x12 scatter diagram. Its outside border is filled with zeros for drawing purposes (Fig. 6). Recommended bin size is approximately 1m in wave height and 2s in wave period. However, the bin size can be reduced for sheltered sites where a lower range of data exists, as in the case in Fig.6.

The percentage of occurrence of each Hs/Tp pairs is calculated. The contour plot is drawn (Fig. 7) using an appropriate contour scale, based on the maximum values in the percentage of occurrence matrix. A maximum of six curves could be plotted for clarity reasons, each curve corresponding to a range of percentage of occurrences. The last range can be corresponding to all values above the last range. For example, a point on this plot between a 3% and 6% curve means that between 3% and 6% of the measured sea states were occurring in the range of Hs and Tp values delimited by the grid.

Statistical wave data are interpolated to be occurring at the same time step than the mooring load time series.

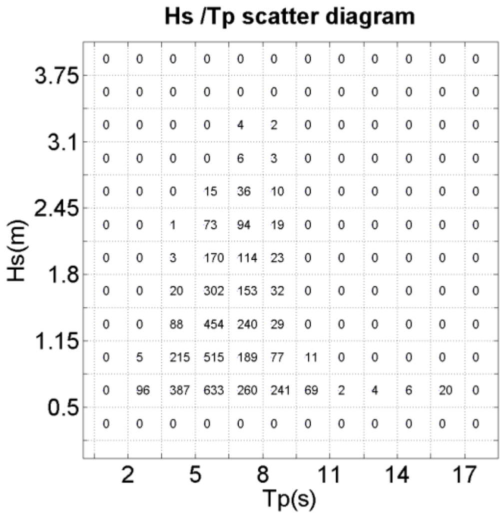
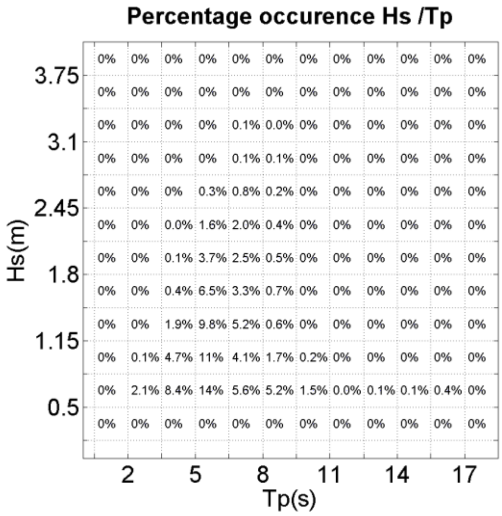


Fig. 6 Example of scatter diagram at SWMTF

(a)



(b)

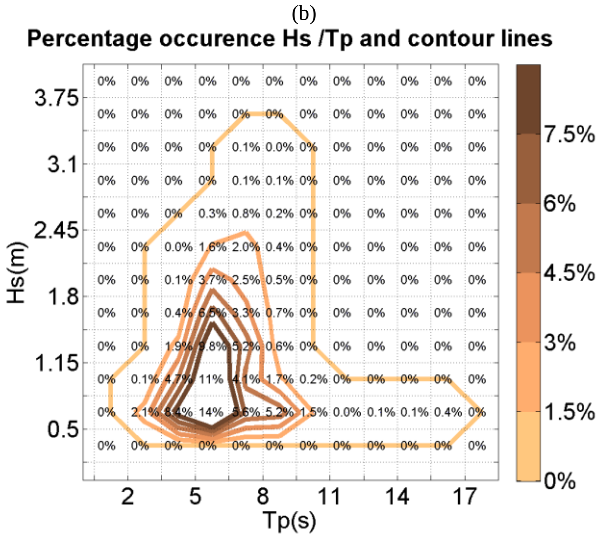


Fig. 7 Example of joint probability distribution of Hs/Tp (a) and its contour plot (b) at SWMTF

B. Selection of extreme mooring loads

Extreme mooring loads are selected in the whole dataset of mooring loads. An extreme mooring load is defined as a mooring load with an amplitude which is significantly higher than the other mooring loads occurring at similar time.

A Peak Tension Threshold K is introduced to isolate extreme mooring loads. K is compared to the standard score of a dataset of several minutes of mooring loads. The standard score (eq 3) of a dataset gives the difference between the maximum and the mean in units of the standard deviation and allowed the comparison of a) of the dynamic part of the mooring load: the amplitude of the maximum mooring load minus the mean mooring load which is the mooring line pretension, or static load, and b) of the dispersion, or spreading, of the mooring loads at this time.

$$S_{max}(x) = \frac{\max(x) - \bar{x}}{\sigma_x} \qquad (3)$$

With S_{max} the standard score of the maximum, $\bar{x}$ the mean of x and σ_x the standard deviation of x. Datasets with a standard score over K indicate that a peak event occurred during this dataset.

A Minimum Tension Threshold τ is introduced and datasets with a maximum mooring load below this value are not considered as extreme. The Minimum Tension Threshold τ is aiming to remove events in a calm sea state which are not relevant for this study, such as collisions or ship wake.

For example, in Fig. 8, the standard score of the maximum was higher than K and the maximum mooring load was higher than τ. An extreme mooring load was then detected. In Fig. 9, the standard score of the maximum was higher than K but the maximum mooring load was lower than τ. No extreme mooring load was detected in this dataset.

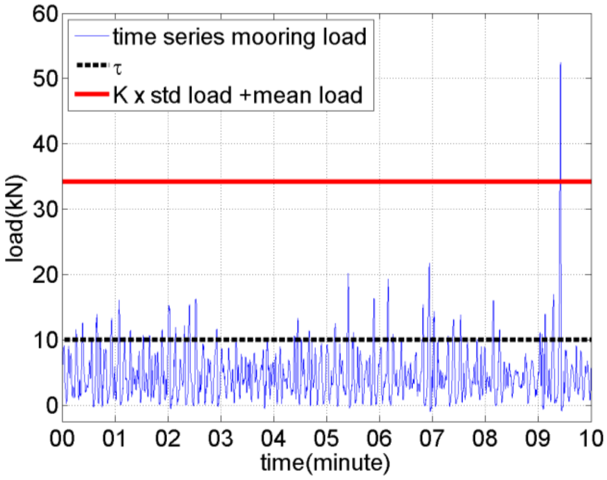


Fig. 8 Example of a 10 minute dataset showing a detected extreme mooring load

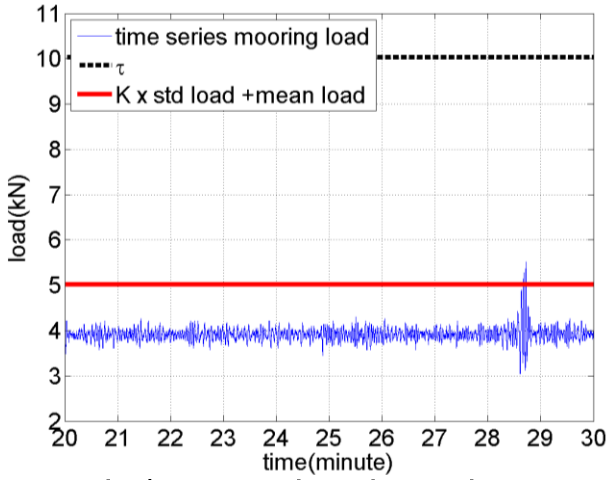


Fig. 9 Example of a 10 minute dataset showing a large mooring load compared to the adjacent mooring loads, but with not sufficient overall amplitude to be considered as an extreme mooring load

Several values of K and τ can be considered. The higher they are the less often the dataset of mooring loads are identified as containing extreme mooring loads. If τ is set to 0kN and K to 0, this means that all datasets are identified as containing extreme mooring loads. Fewer values are selected when τ and K are higher. A mooring system with a high number of mooring lines, or in a quieter environment will be less likely to observe extreme mooring loads at similar Peak Tension Threshold K and Minimum Tension Threshold τ. That is why K and τ have to be chosen depending of the facility parameters such as number of mooring lines, environment, mooring compliance, and of the severity of selected extreme mooring loads. The same values for K and τ are applied to all mooring lines.

For each 10 minute mooring load time series, the maximum value and the standard score were calculated. If the maximum value and the standard score were higher than τ and K respectively (Fig. 10), then an extreme mooring load was detected. The interpolated wave data Hs_{peak}/Tp_{peak} corresponding to a dataset containing an extreme mooring load were recorded.

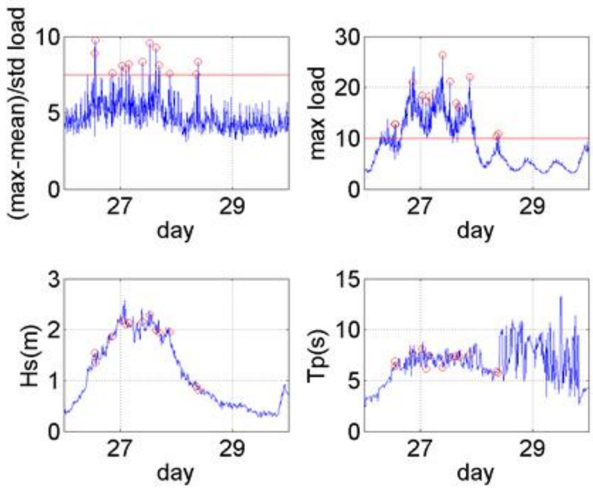


Fig. 10 Detection of extreme mooring loads over several days: top left comparison of standard score of mooring load with K, top right, comparison of maximum mooring load with τ, bottom: waves conditions

C. Analysis of selected extreme mooring loads and their corresponding environmental conditions

The joint probability distribution of Hs_{peak}/Tp_{peak} (eq 4) is calculated and a contour plot is drawn to summarise the results. The envelope of the Hs/Tp joint probability distributions is added to this plot.

$$JPDp_{i,j} = \frac{\sum_{peak=1}^{nb\_peak} \left\langle \begin{matrix} Hs_0 + (i-1)Hs_{bin} \le Hs_{peak} < Hs_0 + iHs_{bin} \\ \text{and} \\ Tp_0 + (j-1)Tp_{bin} \le Tp_{peak} < Tp_0 + jTp_{bin} \end{matrix} \right\rangle}{nb\_peak} \quad (4)$$

With JPDp the joint probability distribution, Hs_{peak} and Tp_{peak} the wave conditions which were identified during an extreme mooring load.

IV. Experimental Results

In this section the key results of the assessment of wave conditions associated with extreme mooring load conditions are presented at the SWMTF site. Firstly the wave conditions are assessed, by plotting the contour plot of the joint probability distribution of the measured wave conditions. Then extreme mooring loads are detected and the contour plot of the joint probability distribution of the wave conditions associated with such extreme mooring loads is determined.

Hs, Tp, and the mean, max and standard deviation of mooring load data have been collected and corrected at the SWMTF. The data used for this analysis were recorded continuously between the 1th of October 2010 and the 31th of December 2010.

A. Environment

The measured wave climates can be classified in 39 sea states, classified in bins of 0.325m Hs_{bin} and 1.5s Tp_{bin}, with Hs_0 equal to 0.5m and Tp_0 equal to 2s. The contour plot of the joint probability distribution of Hs and Tp (Fig. 11) indicates that most of the wave climates occurred for Hs below 2.1m and Tp below 9.5s, with a maximum Hs over 3m.

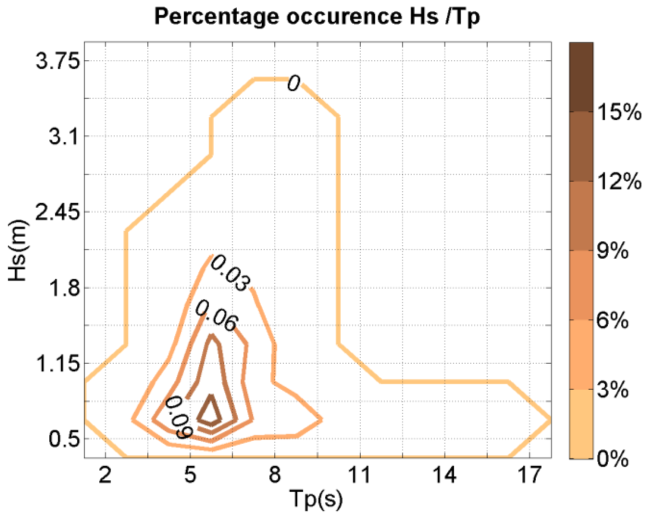


Fig. 11 Contour plot of the joint probability distribution of Hs/Tp at SWMTF

B. Extreme mooring loads

For each 10 minute dataset the mooring load summary data (maximum, mean, and standard deviation) are calculated and their corresponding wave conditions Hs and Tp are interpolated to give values at the same time as the mooring load data. Extreme mooring loads are detected by a) calculating the standard score of the mooring load and comparing it to K, chosen as equal to 7.5 and b) by comparing the maximum mooring load with τ, chosen as three times the average during the whole deployment of the mean mooring load values of each 10 minute dataset. Once these extreme mooring loads are detected, the corresponding wave conditions are saved in the variables Hs_{peak} and Tp_{peak}. The joint probability distribution of Hs_{peak} and Tp_{peak} (Fig. 12) indicates that extreme mooring loads occurred most of the time for 1.5m<Hs<3.3m and 4s<Tp< 9s on line 3. It also shows that the 30 mooring loads with the highest amplitude occurred in a similar range of value.

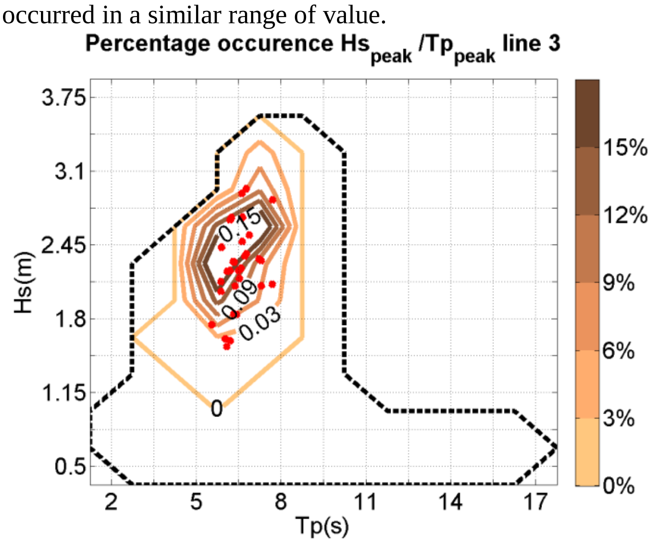


Fig. 12 Joint probability distribution of Hs_{peak}/Tp_{peak} on mooring line 3 at SWMTF (coloured solid lines), envelope of the joint probability distribution of Hs/Tp at SWMTF (black dashed line), and 30 mooring loads with the highest amplitude(red dots)

V. DISCUSSION

A. Sea states and load measurements

The joint probability distribution of Hs_{peak}/Tp_{peak} (Fig. 12) is compared with the joint probability distribution of Hs/Tp (Fig. 11). For a given range of Hs/Tp values, a small value in the joint probability distribution of Hs/Tp associated with a large value in the joint probability distribution of Hs_{peak}/Tp_{peak} means that this range of Hs/Tp values is likely to induce extreme mooring loads.

The number of occurrences of extreme mooring loads relatively to the wave conditions indicates that extreme mooring loads are more likely to occur for large Hs inside the wave scatter diagram, but not necessarily extreme Hs on the envelope of the wave scatter diagram. The mooring loads with the largest amplitude also occur for this same range of Hs.

B. Standards

These results indicate the importance of adapting the available oil and gas mooring standards, such as DNV-OS-E301 [1], to highly dynamic responding moored structures, such as MEC, as for example undertaken by IEC [6]. In particular, DNV-OS-E301 recommends running design calculations for sea states which are on the 100-year Hs/Tp wave scatter diagram envelope of the installation location. The results presented here suggest that it would be more appropriate to consider several additional Hs/Tp combinations within the Hs/Tp wave scatter diagram to assess extreme mooring loads in the design stage. As observed at the testing facility, the extreme mooring loads were not always occurring on the Hs/Tp wave scatter diagram envelope, but within the scatter diagram. This is caused by the highly dynamic response of floating motion dependent MEC devices, which are highly sensitive to wave frequency excitations, which is not the case of large offshore structures which are considered in oil and gas mooring standards.

VI. CONCLUSION

This paper presented some results of long term sea trial investigations of a dynamically responding moored structure and its wave conditions. The aim of this study was to assess the influence of wave conditions on extreme mooring loads. This study has shown that wave conditions not along the envelope of a scatter diagram are more likely to induce extreme mooring loads with large amplitude. The results suggest that traditional offshore standards have to be adapted for MEC technologies because of their highly dynamic behaviour as well as the type of coastal location they are installed. This means that more wave conditions have to be considered for the design phase of such systems, in order to include a large range of Hs/Tp combinations, not only on the envelope of the wave scatter diagram, but also inside the scatter diagram. Several peak periods Tp have to be investigated, together with several Hs values, since extreme mooring loads may occur at high but not extreme values of Hs.

A limitation of these results is that only one test site is used for this study, with only one multi-leg catenary mooring system, when other mooring configurations are also developed for MEC technologies ([7]).

The results presented here will serve as a base for more extreme mooring load analysis looking at all mooring lines of the mooring system presented in this paper in order to investigate directionality effects. Another MEC device will also be investigated. [8]

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